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ROYAL SIGNALS & RADAR ESTABLISHMENT

APPLICATION OF PHASE CONJUGATION TO IMAGE AND SIGNAL PROCESSING

Author: C L West

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AUTHOR: C L West

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SUMMARY

Some of the many potential applications of optical phase conjugation include real time adaptive optics, optical signal processing (in the time or spatial domain), image processing and optical computing. Some of the salient features of optical phase conjugation and the more important signal and image processing functions that one may demonstrate using these techniques will be described in this Memorandum.

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1 INTRODUCTION

Real time information processing of electromagnetic fields can be realised using the technique of nonlinear optical phase conjugation[1-5,18]. This technique is all optical and is free from electromechanical or electronic networks. Such systems can possess much greater spatial and/or temporal bandwidths than their conventional counterparts, reducing system complexity as well as the cost, size and weight. There are many areas to which this technology has been directed including optical computing, real time image and temporal signal processing, real time adaptive optical systems, coherent image amplification, pointing and tracking, filtering, laser fusion and optical communication systems. This Memorandum will address some of these potential applications in more detail and report on the measurement of some of these effects taken at RSRE, Malvern.

2 PHASE CONJUGATION : BASIC DEFINITIONS

Before we proceed further it is necessary to define what is meant by a phase conjugate replica of an incident waveform. It is convenient to consider a probe wave

$$\underline{E}_p(\underline{r},t) = \tfrac{1}{2}\,\underline{\varepsilon}_p(\underline{r})\exp(i(\omega t-\underline{k}_p\cdot\underline{r})) + c.c \tag{1}$$

where $\underline{k}_p$ is the wavevector of the wave and $\underline{\varepsilon}_p(\underline{r})$ is the complex amplitude of the field (slowly varying) which contains the spatial information of the field as well as the polarisation information. The phase conjugate of such a wave is defined by

$$\underline{E}_c(\underline{r},t) = \tfrac{1}{2}\,\underline{\varepsilon}_p^*(\underline{r})\exp(i(\omega t+\underline{k}_p\cdot\underline{r})) + c.c \tag{2}$$

This conjugate wave is at the same frequency as the probe beam but has a spatial complex amplitude that is the complex conjugate of that corresponding to the probe beam. From equations (1) and (2) we can show that the two waves are related by the equation

$$\underline{E}_c(\underline{r},t) \rightarrow \underline{E}_p(\underline{r},-t) \tag{3}$$

The conjugate wave thereby propagates as if it were a 'time-reversed' replica of the probe beam. This property is useful when describing some special features of the phase conjugate reflector. In Figure 1 we show the difference between a conventional plane mirror and a phase conjugate reflector. The ordinary mirror merely redirects the diverging optical beam whereas the phase conjugate mirror reflects the light so that it retraces the incident wave in a time reversed sense back to the initial point source. (In addition the ideal lossless phase conjugate mirror can be shown to reverse all the quantum numbers of the incident photon. The phase conjugate mirror therefore experiences no linear or angular momentum transfer from the incident photons and is free from radiation pressure and torque.)

In a propagating medium whose permittivity is real (lossless) and linear the phase conjugate can be shown to be a valid solution of Maxwell's equation on a point to point basis. In such a medium it is therefore possible to restore aberrated wavefronts to their initial state using a phase conjugate mirror (Figure 2). This effect can be more simply demonstrated by considering a medium which has a simple stepped index profile as shown in Figure 3. After a single pass of the glass slab there is a phase lag in the part of the wave that has passed through the higher index part of medium. After reflection from

a phase conjugate mirror the phase lag is turned into a phase advance of equal magnitude which is then slowed down in the second pass of the slab to restore the original wavefront. If such a beam is reflected by a conventional mirror the phase lag is maintained upon reflection and doubled on its second pass of the medium.

3 PHASE CONJUGATION USING NONLINEAR OPTICAL TECHNIQUES

There are many ways in which a phase conjugate reflector can be realised using the nonlinear optical techniques. In this Memorandum I shall concentrate on a particular elastic photon interaction called degenerate four wave mixing (DFWM), although alternative techniques are discussed in Appendix A. In four wave mixing an output field which is the complex conjugate on one of the input fields is generated by the nonlinear interaction of three incident waves. In contrast to some other techniques, for DFWM the fundamental interaction is not limited to a small class of materials of particular symmetries, but only depends on the presence of a non-zero third order susceptibility[22]. The third order nonlinear polarisation[22] generated by the three incident waves in the medium is defined by

$$(P_{NL})_i = \chi^{(3)}_{ijk\ell}\ \underline{E}_j(\underline{r},t)\ \underline{E}_k(\underline{r},t)\ \underline{E}_\ell(\underline{r},t) \tag{4}$$

This acts as a source term in Maxwell's equation

$$\nabla_\Lambda \nabla_\Lambda \underline{E} = -\mu_o \sigma \frac{\partial \underline{E}}{\partial t} - \mu_o \varepsilon_o (1+\chi^{(1)}) \frac{\partial^2 \underline{E}}{\partial t^2} - \mu_o \frac{\partial^2 P_{NL}}{\partial t^2} \tag{5}$$

where $\chi^{(1)}$ is the linear susceptibility ($\underline{P} = \varepsilon_o \chi^{(1)} \underline{E} + \underline{P}_{NL}$). Although some terms in the expansion of equation (4) may have valid solutions for specific directions (eg all beams colinear) the only term which is applicable for general interaction geometries is (Figure 4)

$$P_{NL} = \tfrac{1}{2} \chi^{(3)}\ \underline{\varepsilon}_1(\underline{r})\ \underline{\varepsilon}_2(\underline{r})\ \underline{\varepsilon}_p^*(\underline{r})\ \exp(i(\omega_1+\omega_2-\omega_p)t - (\underline{k}_1+\underline{k}_2-\underline{k}_p)\cdot\underline{r}) + c.c \tag{6}$$

In DFWM we have the further constraint that $\omega_1 = \omega_2 = \omega_p$ and $\underline{k}_1 = -\underline{k}_2$, hence equation (6) reduces to

$$P_{NL} = \tfrac{1}{2} \chi^{(3)}\ \underline{\varepsilon}_1(\underline{r})\ \underline{\varepsilon}_2(\underline{r})\ \underline{\varepsilon}_p^*(\underline{r})\ \exp(i(\omega t+\underline{k}_p\cdot r)) + c.c \tag{7}$$

where the three waves are assumed to be copolarised and $\chi^{(3)}$ is thereby taken as a scalar quantity.

The process of DFWM as defined in equations (5) and (7) applies for probe beams with arbitrary input angles. The interaction can therefore time reverse the propagation of an arbitrary input probe wave (at frequency ω). It has three other possible effects: amplification of the conjugate wave; amplification of the probe wave and optical parametric oscillation. The ability of DFWM to exhibit amplification can be seen clearly by considering the quantum viewpoint of the effect (Figure 5). In this description of DFWM the field amplitudes are quantised in terms of a photon number for each state

$$\psi_i = |n_1, n_2, n_p, n_c\rangle \tag{8}$$

The interaction Hamiltonian $\underline{P}_{NL}\cdot\underline{E}$ is written in terms of creation (a^+) and annihilation (a) operators[23] and has the form

$$\propto a_1^+ a_2^+ a_p a_c$$

Then the transition rate (Γ) can be defined (using Fermi's golden rule) as

$$\Gamma \propto |\ \ |^2 \propto |\langle n_1, n_2, n_p, n_c\ a_1 a_2 a^p a_c | n_1, n_2, n_p, n_c \rangle|^2$$

where the primed photon occupation numbers correspond to the final output photon eigenstate. Non-zero transitions occur for the following condition

$$n_1 = n_1 - 1$$

$$n_2 = n_2 - 1$$

$$n_p = n_p + 1$$

$$n_c = n_c + 1$$

resulting in the annihilation of a photon from each pump beam and the creation of a photon in <u>both</u> the probe and the conjugate beam. Oscillation is also seen to be possible as Γ can be non-zero even if n_p and n_c equal zero.

In photorefractive materials[5,19-21] such as Bismuth Silicon Oxide (BSO: $Bi_{12}SiO_{20}$) the process of DFWM can be considered as equivalent to real time holography[24]. The probe beam interferes with one or both of the pump beams to create an interference pattern in the material. In the regions of high intensity carriers will be excited into the conduction band from luminescence centres. These carriers diffuse or drift into the regions of lower intensity and become trapped at defect sites. The field which results from the charge separation modulates the refractive index of the material using the electro-optic effect and produces a phase grating (Figure 6). The grating which is active in a particular experiment (Figure 7) can be selected by changing the coherence and intensity relationshops between the three optical input beams.

The interference pattern produced by the interaction between the two beams E_1, E_p has the form

$$T \propto (E_p + E_1)(E_p^* + E_1^*)$$

$$T \propto |E_p|^2 + |E_1|^2 + E_p E_1^* + E_1 E_p^* \tag{12}$$

This interference pattern modulates the refractive index of the medium as described above and the phase grating is read out by the read beam, E_2 ($= E_1^*$) (see Figure 8)

$$E_c = TE_2$$

$$E_c \propto (|E_p|^2 + |E_1|^2)\ E_1^* + (E_1^*)^2\ E_p + |E_1|^2\ E_p^* \tag{13}$$

The first term on the right is proportional to the intensity of the incident field; the second term is phase mismatched and will not radiate in a thick hologram. The remaining term corresponds to the time reversed phase conjugate replica of the incident field and demonstrates the common feature of holography and phase conjugation. In the present case, of course, there is no need to process photographic plates and the process is real time.

There are however some differences between DFWM and holography. In an isotropic medium the vector form of the nonlinear polarisation beams[25]

$$P_{NL} = \tfrac{1}{2}\, A(\underline{E}_1 \cdot \underline{E}_p^{*})\, \underline{E}_2 + B(\underline{E}_2 \cdot \underline{E}_p)\underline{E}_1 + C(\underline{E}_1 \cdot \underline{E}_2)\underline{E}_p) \quad + \text{c.c} \qquad (14)$$

The first two terms are analogous to the grating picture described above and shown in Figure 7. These terms require that the polarisation of the fields in the dot product have a non-zero overlap. The third term in equation (14) has no holographic analogue. The dot product is between the two pump waves and is not equivalent to a spatial interference pattern but produces a temporally modulated grating which is stationary in space. The probe beam is scattered off this breathing grating (at 2 ω) and can get a conjugate wave even if the probe beam is orthogonally polarised with respect to both of the pump beams. In this case the last term must exist ($C \neq 0$) and the pump beam must have a non-zero overlapping polarisation component.

4 USES OF PHASE CONJUGATION

Three major areas of possible use for phase conjugate techniques exist: spatial processing, temporal processing and resonator structures. Each area individually is extremely diverse and this Memorandum will hope to cover the major subsets of the signal and image processing areas.

4.1 SPATIAL INFORMATION PROCESSING

Two main areas of spatial information exist: distortion correction and mathematical operations. In predetection distortion correction[2] we note that a laser beam transmitted through a medium will spread due to its initial finite size. If diffraction were the only factor present the final size of the beam would be diffraction limited and only waveguiding would result in tighter constriction. Further distortions exist due to refractive index changes in the propagating medium (atmospheric turbulence, thermal blowing). These distortions can be compensated by the transmission of a probe beam in the reverse direction to that required for image transmission. This senses the total distortion in the path and upon reflection by a phase conjugate mirror will contain the required phase distortion to compensate the returning image[12]. Imaging of objects through turbulent medium[26,27] may be realised by deriving a reference phase distortion from a glint on the far object; after several iterative passes between the glint and the phase conjugate mirror a reference wavefront is available which corresponds to a point source in the object plane. One example of this use is in laser fusion (Reference 28, Figure 9). In this application the pellet of fusion material is illuminated by a weak source. The scattered light from the target is partially collected by the laser optics and partially amplified. The phase front information is conjugated and further amplified and the phase reversal automatically targets the high energy laser beam on to the target. In practice it is desirable to slightly offset the return beam to compensate for the distance that the pellet falls in the round trip time. This can be realised using the system displayed in Figure 10. The phase conjugate return is chosen to be orthogonal in polarisation to that of the incident probe beam and thereby can be redirected using polarisation beam splitters and tilted mirrors to the optimum return beam position. This allows for minor compensation of return directions in slowly varying operating medium where it can be assumed that the aberrations experienced by the probe beam are similar to those experienced by the return conjugate beam.

In the field of photolithography there is often a requirement for diffraction limited resolution over a flat field of dimensions in access of 10 cm. In addition it is desirable to extend the lifetime of photolithographic masks by ensuring that the process does not require intimate contact (as is normal in the Si area) between the mask and the photoresists. A possible projection tool for use in photolithography using phase conjugation is shown in Figure 11. This technique has been demonstrated[29] with a resolution of 800 lines/mm over a 6.8 mm^2 field with feature sizes of 0.75 μm.

A further application of phase conjugate image transmission concerns image transmission down a multimode fibre[30]. The image is distorted due to modal distortion, differential modal attenuation and intermode scattering. The first of these distortions can be compensated for in two ways. In the first method a probe beam is sent down the fibre to sense the aberration that the light experiences and it is this light which is used to encode the signal light which counter-propagates down the same fibre. Alternatively a pair of matched fibres can be used to transmit the image where the distortions of the first fibre are compensated for using a phase conjugation element before transmission down the remaining fibre. In this case the phase conjugate mirror is sited at the midpoint of the transmission system.

The ability of coherent optical processing to perform linear and nonlinear computational operations has been reviewed by Lee[7]. Addition, subtraction, differentiation and generalised orthogonal transformations using these techniques was discussed. One of the most important linear operations that can be performed using coherent optics in a linear system is the Fourier transform (Figure 12). A simple lens provides a Fourier transform relationship between the lens front and back focal planes[31]. Consider the arrangement depicted in Figure 13. The phase conjugate return E_c is proportional to the product $E_p^* E_1 E_2$. But E_1 and E_p are Fourier transforms of the real images e_1 and e_p. Thus the Fourier transform of the conjugate field E_c, e_c, is the correlation of e_p and e_1 convolved with e_2, the Fourier transform of E_2 (applying the Convolution Theorem). For e_c to be just the correlation of e_p and e_1, e_2 must be a delta function; this implies that E_2 must be a plane wave. As with all correlator systems that are reliant on the Convolution theorem and multiplication of Fourier transform planes the system is spatially invariant. The results of correlation experiment with simple shapes is shown in Figure 14. Many authors have demonstrated and discussed convolution and correlation using this technique[1,2,15,16,17] and is hoped that a latter memorandum will address this area of phase conjugation in more detail.

Another series of useful image manipulations can arise from diffraction efficiency effects of the gratings written in a photorefractive material. The reflected intensity from a grating is proportional to $m^2 I_2$ where I_2 is the read beam intensity and m is the modulation index of the grating defined by

$$m = \frac{2\sqrt{I_1 I_p}}{I_1 + I_2 + I_p} \underline{e}_1 \cdot \underline{e}_p^* \qquad (15)$$

$\underline{e}_1$ and $\underline{e}_p$ denote the polarisation vectors of the write beams. There are several ways in which modification of the magnitude of this modulation index can result in edge enhancement (Refs 6,9,13, Figure 15). In one case(6,9) the beam intensities are chosen such that $I_2 < I_1, I_p$. Here the modulation index has the modified form

$$m = \frac{2\sqrt{I_1 I_p}}{I_1 + I_p} \tag{16}$$

Now when $I_1 = I_p$, $m = 1$ and we have a strong grating formed, whereas for any other beam ratio $m < 1$. If an object, in beam 1, is imaged into the four wave mixing medium and the probe beam intensity is set to be intermediate between the dark and light areas of the image then the areas where the intensity is changing between dark and light will go through a region of nearly identical intensity and strong diffraction will occur, producing an edge enhanced image. An alternative approach[9,17] to the same problem is to produce the Fourier transform of the object in the four wave mixing medium and eliminate the low frequency components of the spectrum using an auxiliary beam. The phase conjugate beam will not contain the low frequency components and the re-transformed image will display edge enhancement.

Real time image division has also been demonstrated using similar techniques to the described above. In the case where $I_1 \gg I_2, I_p$ the conjugate wave has an intensity proportional to

$$I_c \propto m^2 I_2 \propto \frac{I_1 I_p}{I_1^2} \cdot I_2$$

If I_p and I_c correspond to uniform distribution then $I_c \propto 1/I_1$ and we can demonstrate image division[8]. It may be possible to use such a technique to perform holographic deconvolution to sharpen or deblurr a blurred image (Refs (10,11). The intensity of a blurred image can be expressed as $g(x',y') = f{*}h$ where $h(x,y)$ is the intensity of the impulse response function of the imperfect imaging system which blurs the object and $F(x,y)$ is the desired object intensity function. Applying the Fourier transform to this equation we get $G = FH$ where G, F and H are Fourier transforms of g, f and h respectively. Thus $f = F^{-1}(G/H)$ and deblurring can be achieved if the image division G/H is the Fourier transform plane can be realised.

4.2 TEMPORAL PROCESSING USING OPTICAL PHASE CONJUGATION

Many time domain signal processing functions can be demonstrated using the techniques of optical phase conjugation: time delay control; logic gating; temporal convolution and correlation; envelope reversal and space to time modulation (demodulation).

The simplest function that can be described using this technique is time delay control[3]. In Figure 16 we see three waves impinging on to the four wave mixing medium. The short pulse E_1 and the probe pulse E_p have the same polarisation and beat to form a moving intensity pattern which modulates the nonlinear refractive index of the medium forming a moving diffraction grating. The initial pulse that we are trying to control enters the medium with orthogonal polarisation to the other beams and is scattered off this moving grating. The timing of this interaction depends on the relative timing of the two beams E_2 and E_1.

One application of this scheme may be an electronically programmable optical delay line where the pulse E_2 may be required to have variable delay and is not accessible to direct control, but we may have control over the pulse E_1. In addition, if all three incident fields are pulsed, logic functions can be demonstrated. Beams may also be pulse shaped by choosing the corect form for the accessible pulses, E_2, E_4. Wavefronts which are time delayed using this technique can be further used as a diagnostic tool in dynamically varying refractive index fields(14).

When orthogonal pumping geometries are employed we can demonstrate temporal modulation, correlation and convolution(3). In Figure 17 two waves with complex envelopes counter-propagate down a nonlinear delay medium. A third CW field impinges on the crystal orthogonal to the first two. The convolution/correlation between the two modulated signals is read out by one of these beams scattering off the moving grating formed by the second beam and the probe. As time progresses the two beams pass through each other and the output at the detector gives the correlation function as a function of time. If coherent detection is employed the optical modulator should have an input where the input "field" is modulated linearly with respect to a voltage or current. If a conventional direct detector is employed then modulations should generate intensities proportional to the current or voltage. For true correlation it must also be noted that the nonlinear medium must be large enough to contain the optical pulses and the timing between the pulses be such that they are both contained within the medium during the correlation.

Wave train time reversal(1) is shown in Figure 18. The incoming wave with its complex amplitude variation enters a nonlinear medium and while it is contained within the medium it is co-illuminated with a strobe pulse which writes into the crystal a holographic fringe pattern that is characteristic of the original wave train. A second pulse, counter-propagating to the first, then reads this grating and a time reversed image of the input waveform is produced propagating in the opposite direction.

The above system can be modified to produce space to time encoders. In Figure 19 a moving fringe pattern is set up between the fie'ds E_p and E_1 in a similar manner to that described in Figure 16. The second orthogonal pump is spatially modulated by a phase and/or amplitude plate in its beam path. (In the figure we demonstrate a quadratic phase plate.) In the absence of such a plate a constant amplitude continuous wave output would be seen counter-propagating to the probe pulse. A phase variation in the plate would result in differential time delays and the conjugate wave would exhibit frequency modulation (quadratic phase would produce a linear chirp output) and amplitude modulation in the plate would result in amplitude modulation of the output beam.

The use of phase conjugation to relay time encoded messages is considered in Figure 20. A probe beam and pump beam write a fixed grating in the nonlinear medium. A second pump beam, which is temporally modulated, is diffracted off this grating and the resultant counter-propagates with respect to the probe beam but contains the temporal encoding of the second pump beam. As it is only the build-up of the grating which is medium dependent, the speed at which data can be transmitted down this highly directional, and thereby covert line, is determined only by the time of transit of the encoded beam through the grating. Several different probes can be used, accessed simultaneously and a possible extension

of the technique could involve high data rate transmission around computers or discrete chips. Data transmission has been demonstrated in excess of 1 Mbit/s (see Figure 21), although in principle the upper frequency limit is much higher. The arguments used above also apply to the spatial correlator (Figure 13). Many reference images can be compared with a slowly varying input scene if configured in the correct sense.

5 CONCLUSIONS

Nonlinear optical phase conjugation has been demonstrated to possess a potential as the key element in adaptive optical systems with applications in optical computing, communications, lensless imaging, fusion and real time image and temporal signal processing. These are all optical interactions which occur in real time free from electromechanical components and electronic free back networks and can provide large spatial and temporal bandwidths may provide a new and exciting generation of device applications. Some major limitations to such a technique would be the present physical size of the phase conjugate element (limiting the size of phase point that can be compensated), the spread of response of the element, the need for coherence between interacting beams (not as critical for fast elements), the availability of the phase conjugating media in parts of the electromagnetic spectrum near visible wavelengths and the non-ideal performance of a phase conjugate mirror which does not exhibit unity gain. The extent to which any of these considerations affect a system will depend intimately on that system's peculiarity and requirements.

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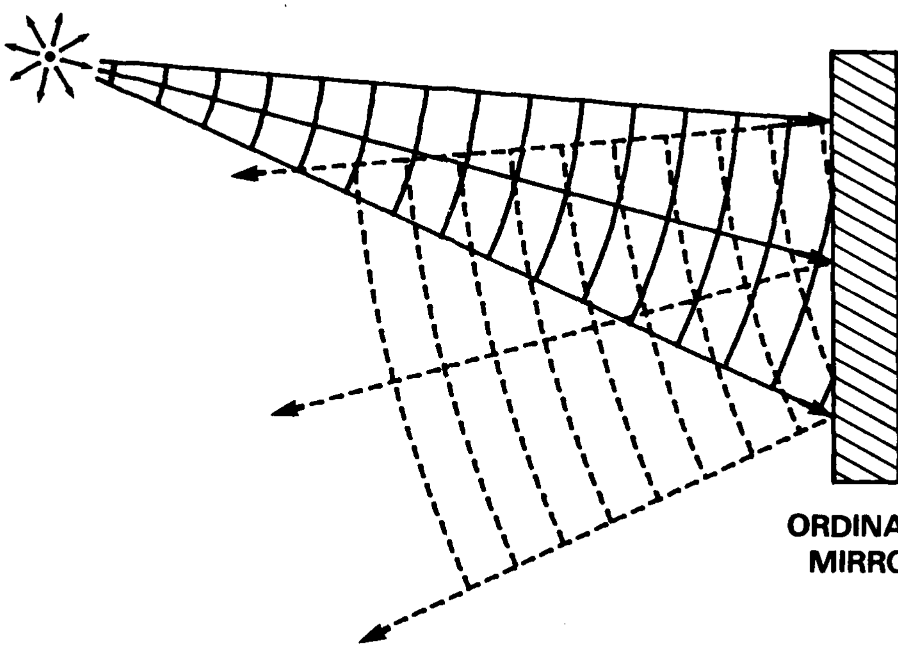
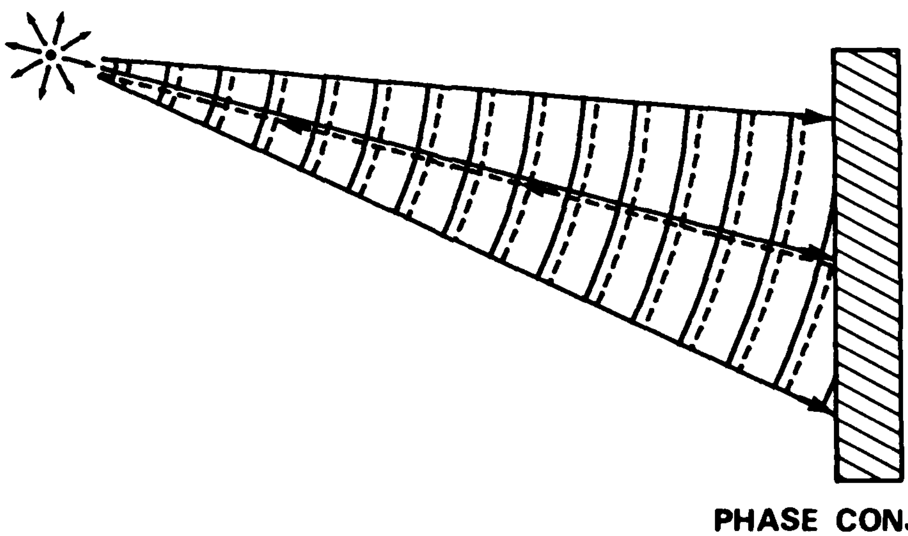
Figure 1. Comparison of the reflective properties of a phase conjugate mirror with that of a conventional plane mirror. The conventional mirror redirects the diverging beam while the phase conjugate mirror reflects the light, so that the reflected beam retraces the incident wave in a time reversed sense.

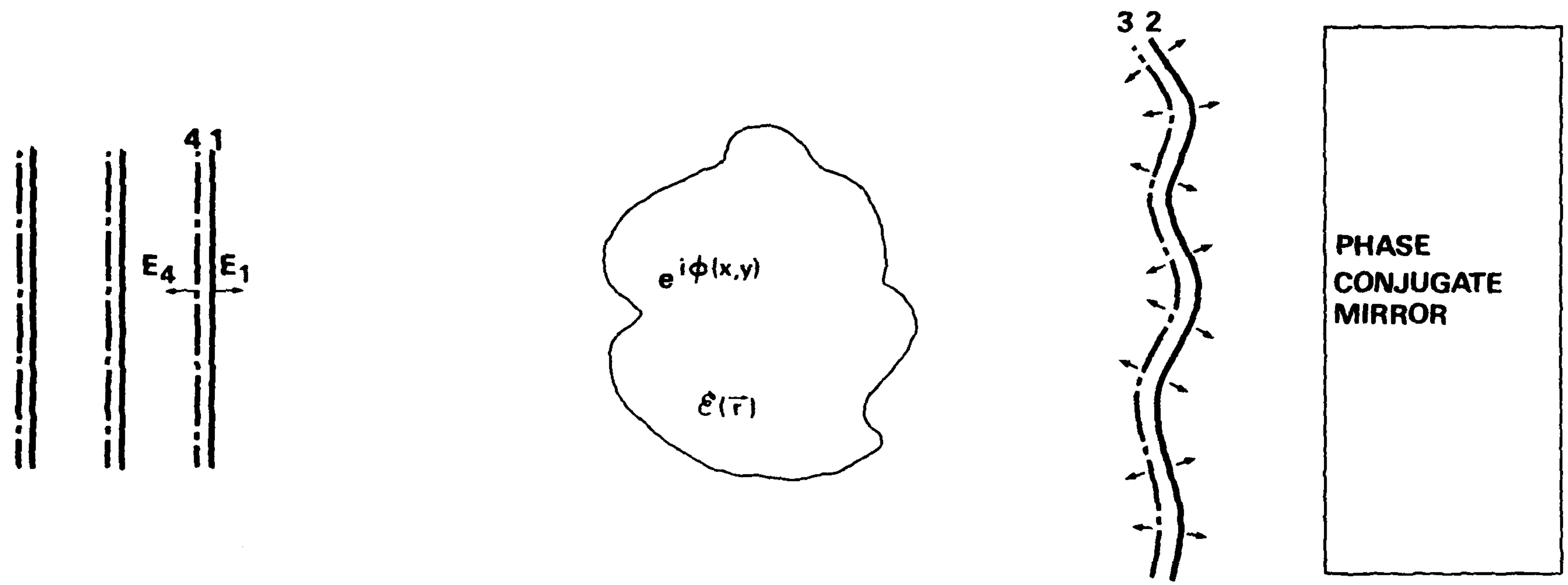


ORDINARY
MIRROR



PHASE CONJUGATE
MIRROR

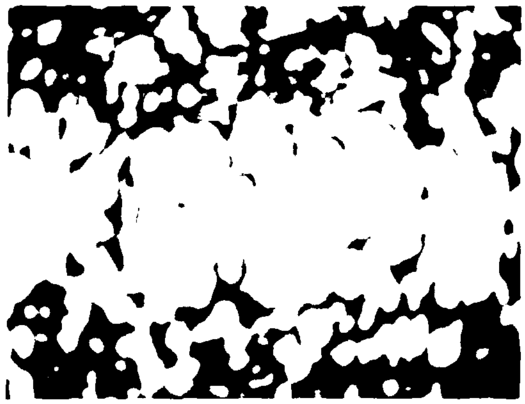
Figure 2a. This figure demonstrates the ability of a phase conjugate mirror to correct the aberration in a beam caused by a medium whose permittivity is real (ie lossless) and linear. The incident beam(1) becomes distorted after traversing a phase aberrator. This wave(2) is reflected by a phase conjugate mirror which time reverses the wavefronts(3). This reflected beam then propagates through the aberrating medium a second time during which the phase distortions are reversed resulting in a fully corrected wave at the initial position, but travelling in the reverse direction.



4 1
E4
E1
eiφ(x,y)
ℰ(r)
3 2
PHASE
CONJUGATE
MIRROR

Figure 2b. Image transmission through a phase distortion. This figure demonstrates the difference in image quality after a double pass through a phase aberration and a reflection by either a conventional plane mirror or a phase distortion has been corrected.

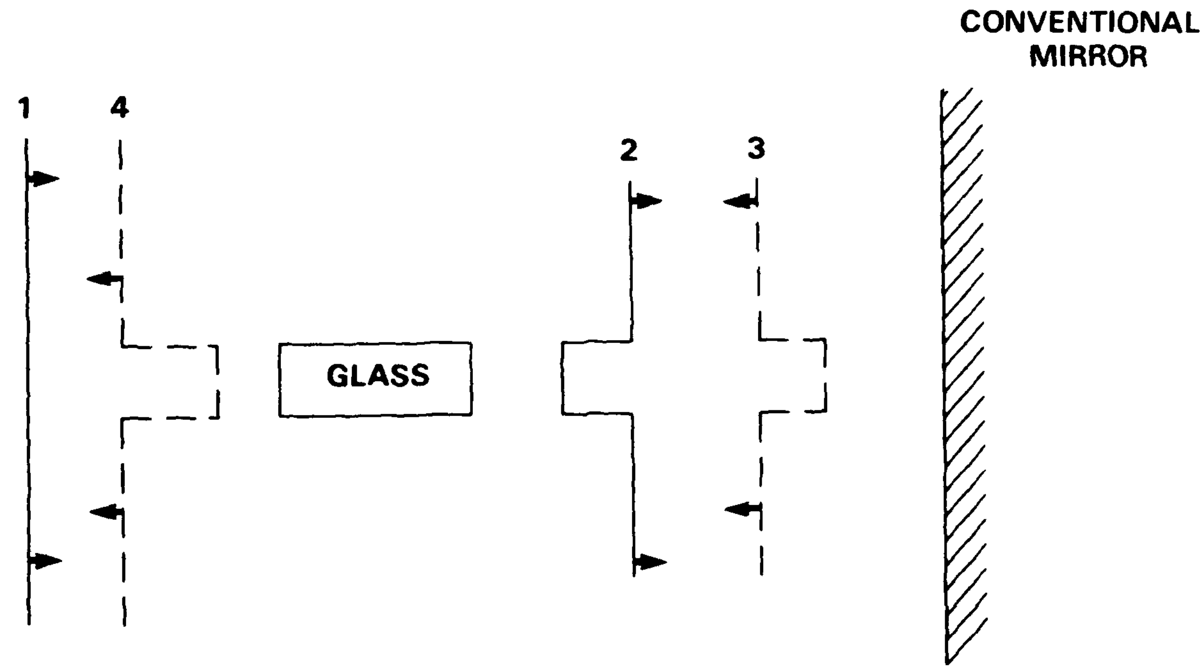
IMAGE TRANSMISSION THROUGH A PHASE DISTORTION



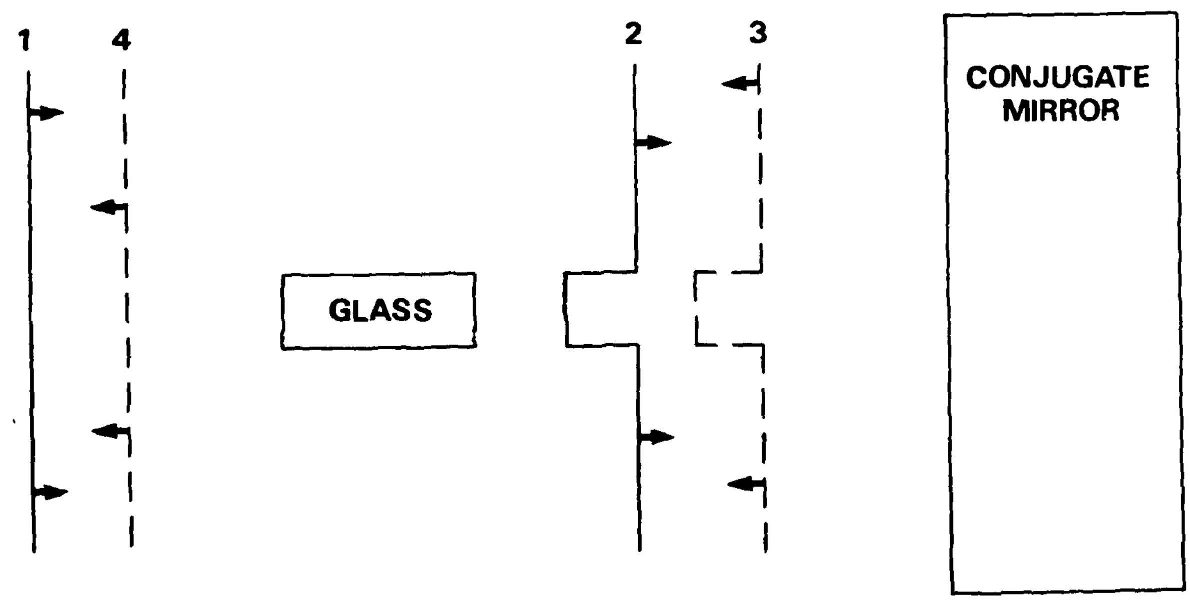
CONVENTIONAL MIRROR

PHASE CONJUGATE MIRROR

Figure 3. Comparison of a conventional plane mirror with a phase conjugate mirror. The plane wavefront(1) incident upon a phase distortor leaves the area with a bulge in its equiphase surfaces(2). After reflection by a conventional mirror(3) and a second pass of the medium the wave has a bulge that is twice the size as for a single pass(4). If a phase conjugate reflector is used the phase lag is turned into a phase advance(3) and this is eliminated by a second pass through the medium(4).


CONVENTIONAL MIRROR
1
4
2
3
GLASS

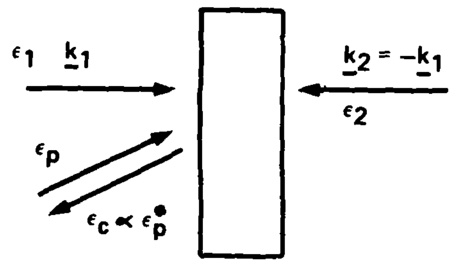
(a)


1
4
2
3
GLASS
CONJUGATE MIRROR

(b)

Figure 4. Degenerate Four Wave Mixing (DFWM). The nomenclature used during this memorandum is depicted in this figure. Beams 1 and 2 are the counter-propagating pump beams. Beam p is a probe which is phase conjugated into beam c.

DEGENERATE FOUR WAVE MIXING (DFWM)



$$P_{NL} = \frac{1}{2} \chi^{(3)} \epsilon_1(\underline{r})\, \epsilon_2(\underline{r})\, \epsilon_p^*(\underline{r}) \exp(i(\omega t + \underline{k}_p \cdot \underline{r})) + cc$$

Figure 5. The quantum viewpoint of degenerate four wave mixing (a). Two counter-propagating pump photons and a third probe photon are incident upon the nonlinear medium. After the interaction the two pump photons have been annihilated and two new photons, travelling in the $\pm z$ direction have been created. There is no linear or angular momentum transferred to the medium.

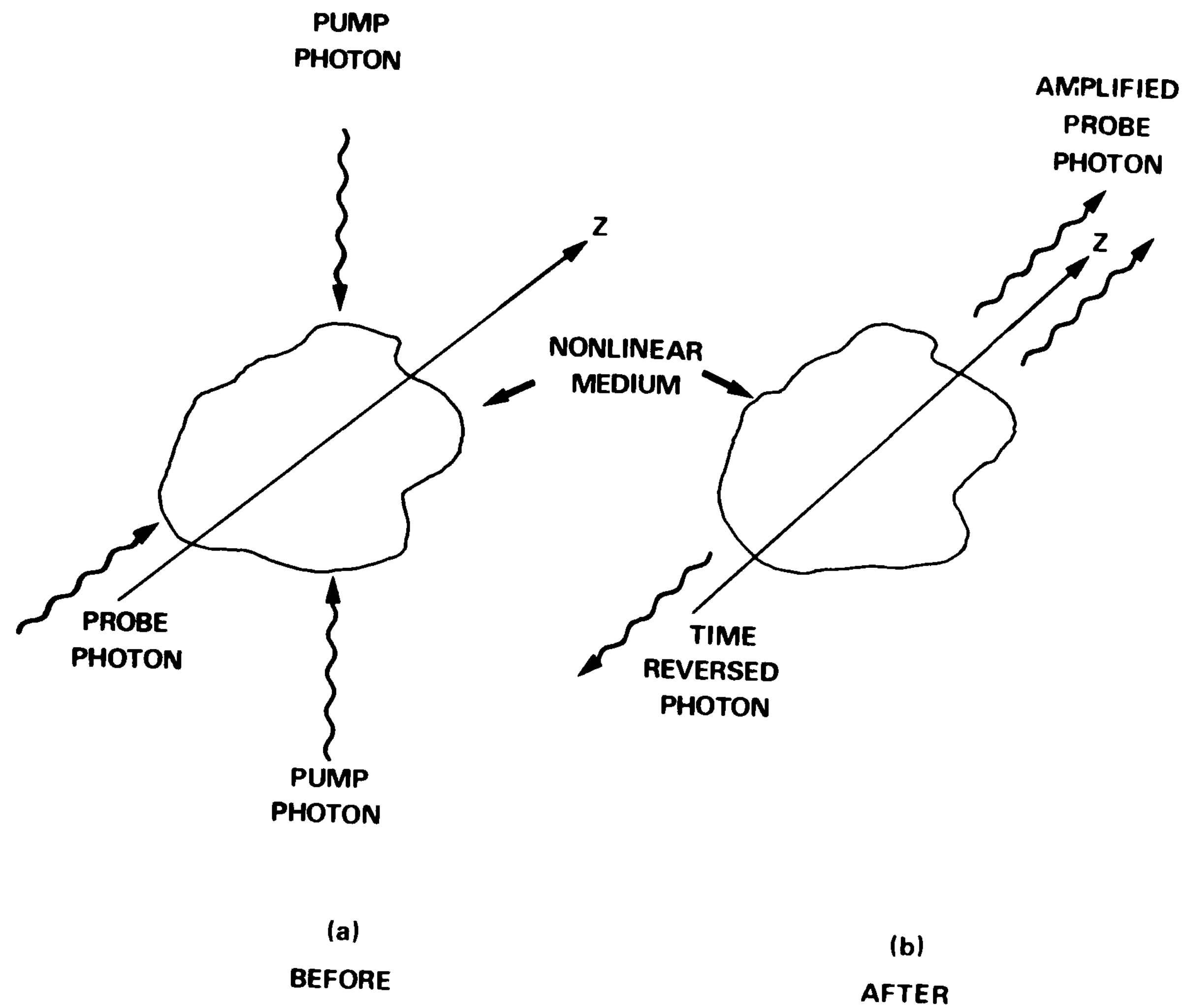

PUMP
PHOTON
AMPLIFIED
PROBE
PHOTON
Z
Z
NONLINEAR
MEDIUM
PROBE
PHOTON
TIME
REVERSED
PHOTON
PUMP
PHOTON
(a)
BEFORE
(b)
AFTER

Figure 6. Formation of a photorefractive index grating. Two beams interact in the medium to produce areas of high and low intensity. In the regions of high intensity cariers are ejected from luminescence centres into the conduction band. These carriers either diffuse or drift into the regions of lower intensity and become trapped at defect sites. The electric field produced by the non-uniform charge distribution then modulates the refractive index via the electro-optic effect.

FORMATION OF A PHOTOREFRACTIVE INDEX GRATING

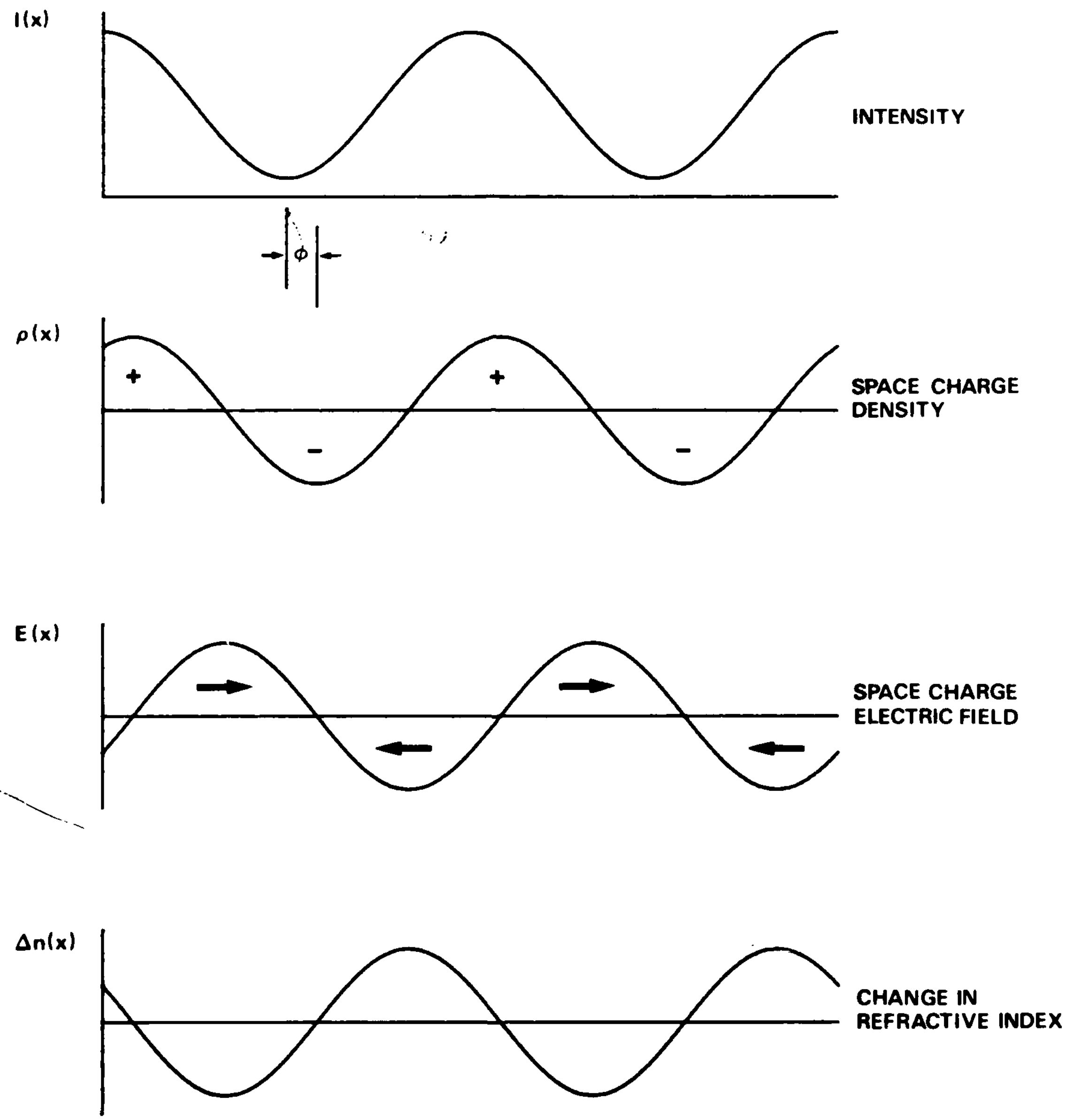
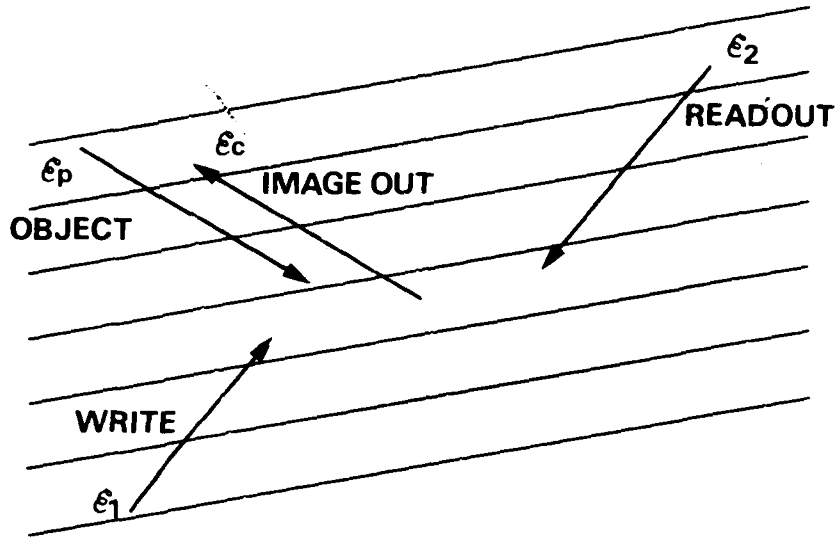
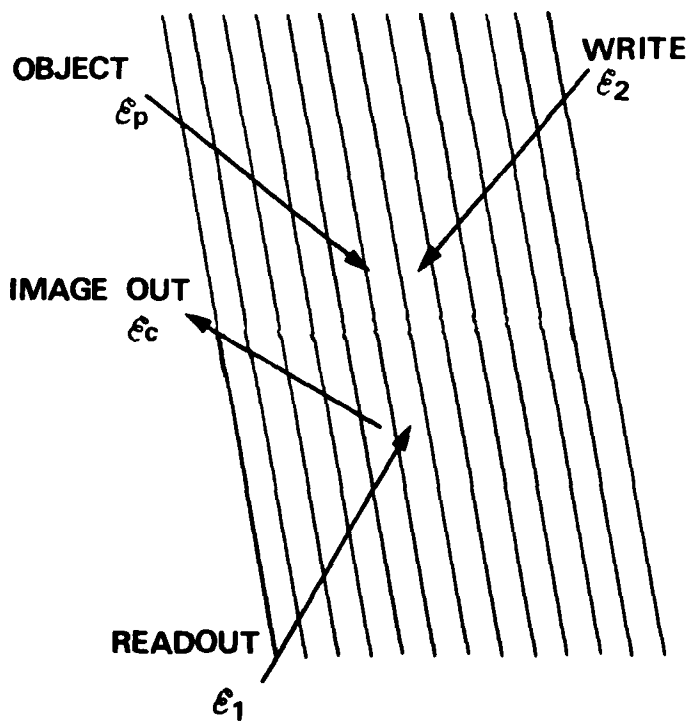


Figure 7. The two spatial gratings present during DFWM in photorefractives. In (a) ε_1 and ε_p interfere to form a large period grating (period d) which is read out by the field ε_2: $d = \lambda/[2\sin(\theta/2)]$. In (b) ε_2 and ε_p interfere to form a small period grating which is readout by wave ε_1: $d = \lambda/[2\cos(\theta/2)]$. The existence of these gratings depend on the relative coherence and polarisation of the write beams.


$\mathcal{E}_2$
READOUT
$\mathcal{E}_c$
$\mathcal{E}_p$
IMAGE OUT
OBJECT
WRITE
$\mathcal{E}_1$

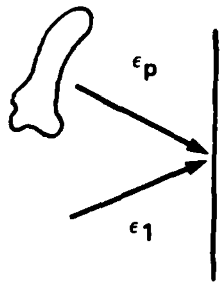
(a)

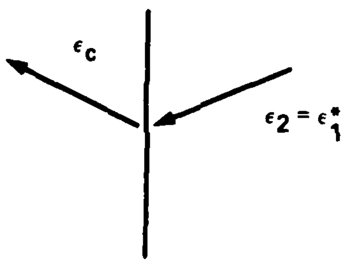

WRITE
OBJECT
$\mathcal{E}_2$
$\mathcal{E}_p$
IMAGE OUT
$\mathcal{E}_c$
READOUT
$\mathcal{E}_1$

(b)

Figure 8. Four wave mixing and holography. In conventional holography a reference beam ε_1 and an object beam ε_p interfere and the result is recorded in a photographic emulsion. The original wavefronts are reconstructed by illuminating with a single reference beam ε_2 ($= \varepsilon_1^*$). The diffracted field is given in the text by equation (13). The third term in the expression corresponds to phase conjugation by degenerate four wave mixing.

FOUR WAVE MIXING AS DYNAMIC HOLOGRAPHY





$$T \propto (\epsilon_p + \epsilon_1)(\epsilon_p^* + \epsilon_1^*)$$

$$T \propto |\epsilon_p|^2 + |\epsilon_1|^2 + \epsilon_p \epsilon_1^* + \epsilon_1 \epsilon_p^*$$

$$\epsilon_c = T\epsilon_2$$

$$\epsilon_c = \underbrace{(|\epsilon_p|^2 + |\epsilon_1|^2)\,\epsilon_1^*}_{1} + \underbrace{(\epsilon_1^*)^2\,\epsilon_p}_{2} + \underbrace{|\epsilon_1|^2\,\epsilon_p^*}_{3}$$

Figure 9. Real time adaptive optical pointing and tracking system for laser fusion. The fuel pellet is irradiated from a weak beam. The scattered light is collected by the input optics, amplified and falls on to a phase conjugate reflector where the phase fronts are reversed. The beam is then further amplified and is directly targeted at the original site. The resulting beam is a diffraction limited and aberration free, intensely focused beam.

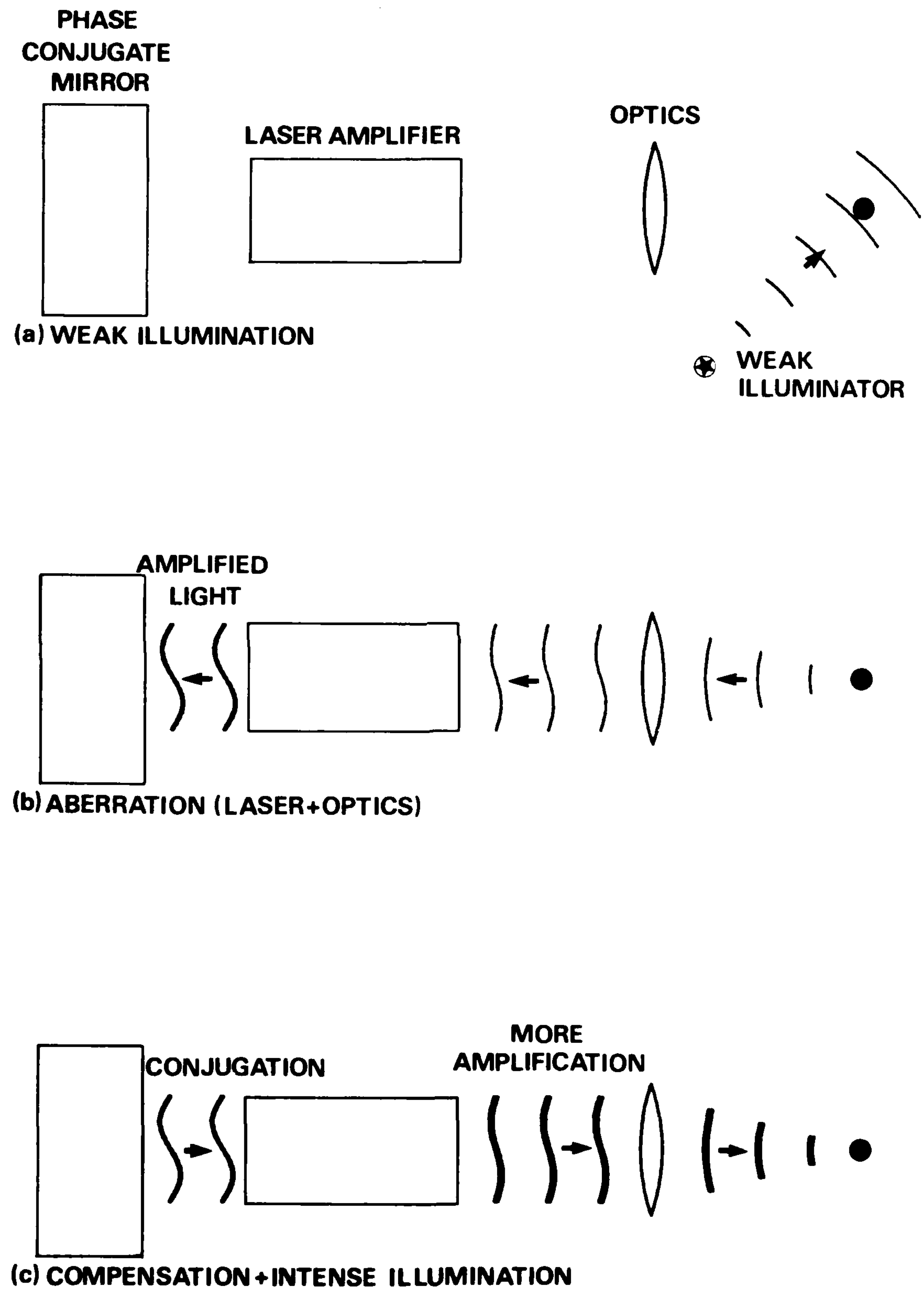
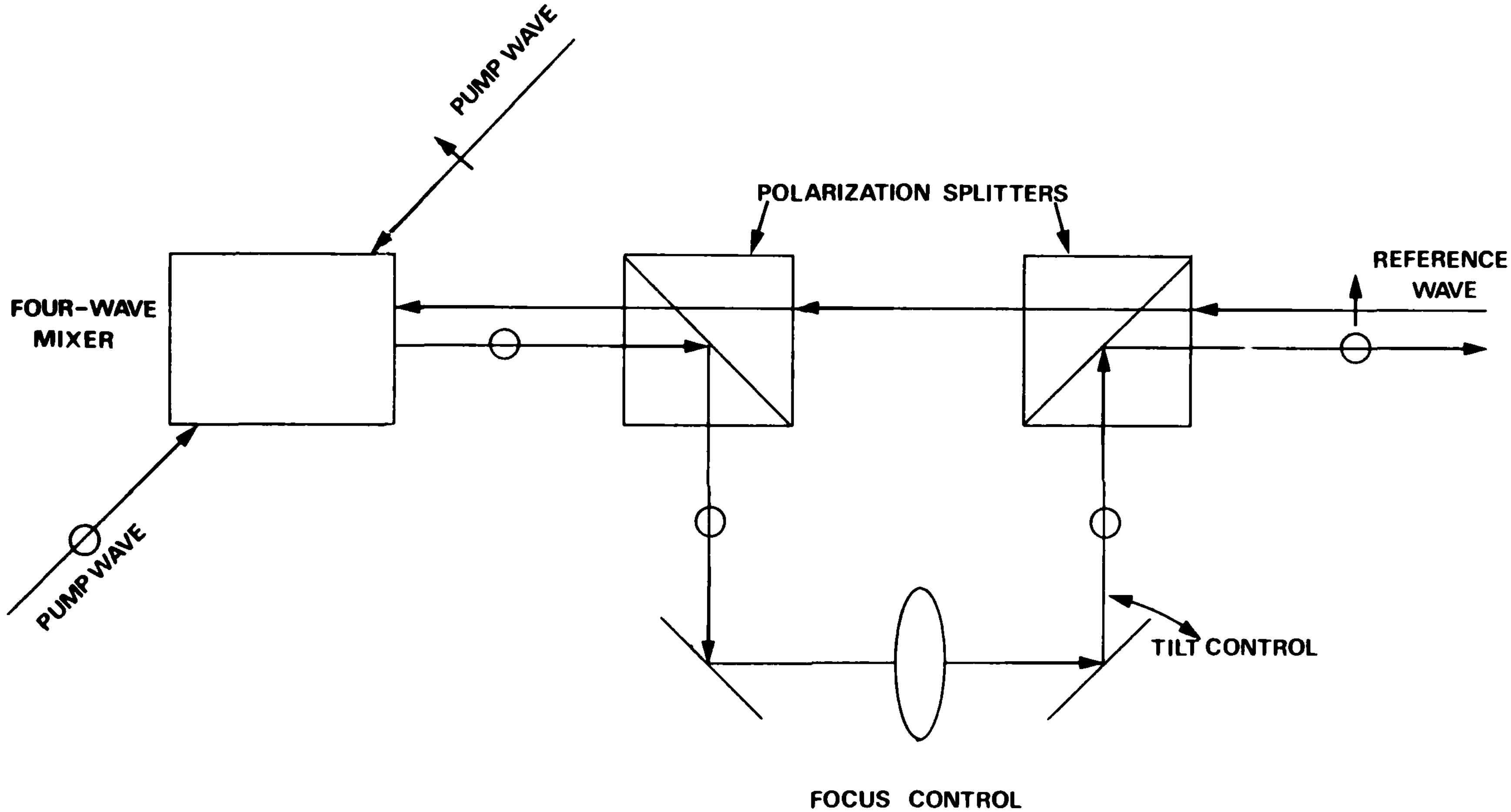

PHASE CONJUGATE MIRROR
LASER AMPLIFIER
OPTICS
(a) WEAK ILLUMINATION
WEAK ILLUMINATOR
AMPLIFIED LIGHT
(b) ABERRATION (LASER+OPTICS)
CONJUGATION
MORE AMPLIFICATION
(c) COMPENSATION+INTENSE ILLUMINATION

Figure 10. In some real time adaptive optical pointing and tracking systems it is necessary to compensate for the round trip time of the optical beams and relative motion between target and source during this time (eg in satellite transmission systems). If the reference and pump waves are of one polarisation and the second pump beam and conjugate replica of the other polarisation the polarisation beam splitters can be used to redirect the conjugate return and allow some redirection. The suitability of such a technique relies in the intermediate medium being slowly varying with respect to aberrations so that the correction made by the phase conjugate reflector is valid.



PUMP WAVE
POLARIZATION SPLITTERS
FOUR-WAVE MIXER
REFERENCE WAVE
PUMP WAVE
TILT CONTROL
FOCUS CONTROL

Figure 11. Photolithographic tool employing phase conjugation. Light passes through the mask and passes through the (optional) amplifier and falls on to a phase conjugate mirror. The time reversed image is further amplified, with phase distortion corrected and is imaged on to the substrate. The image is free from direct mask contact problems, laser speckle and undesirable diffraction effects.

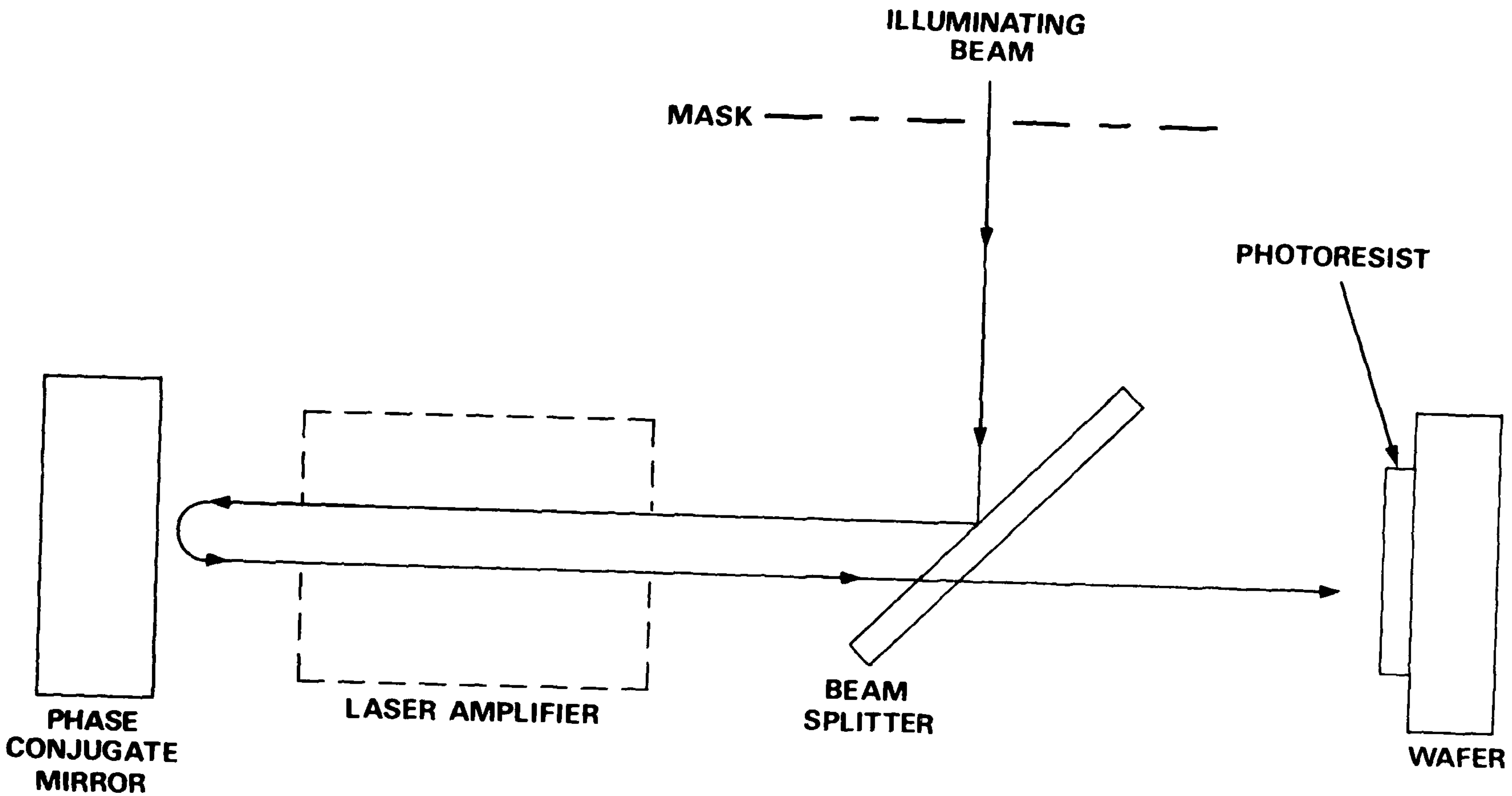
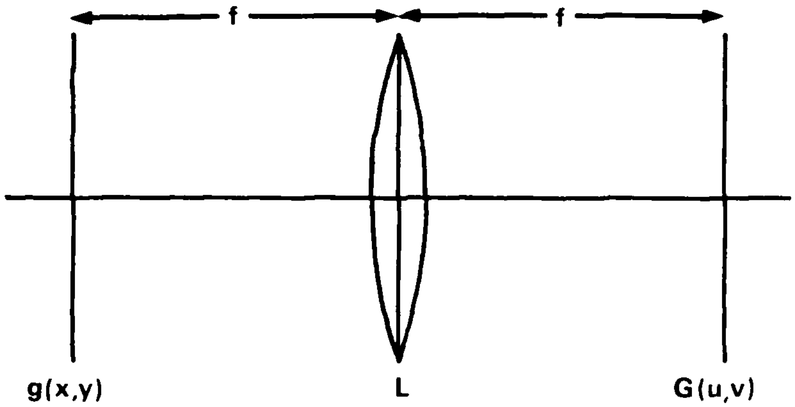

ILLUMINATING
BEAM
MASK
PHOTORESIST
PHASE
CONJUGATE
MIRROR
LASER AMPLIFIER
BEAM
SPLITTER
WAFER

Figure 12. The Fourier transform properties of a lens. A Fourier transform of spatial information exists between the optical information and the lens front and back focal planes.

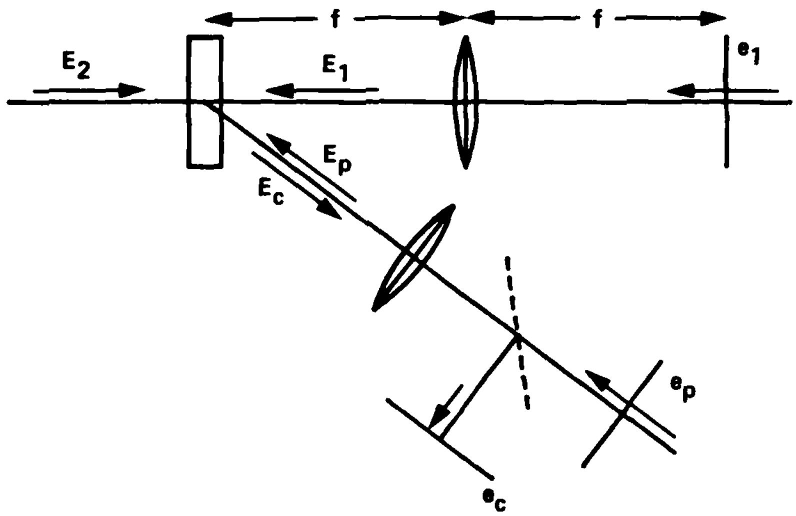


FOURIER TRANSFORM PROPERTIES OF A LENS

A FOURIER TRANSFORM OF SPATIAL INFORMATION EXISTS BETWEEN THE OPTICAL INFORMATION IN THE LENS' FRONT AND BACK FOCAL PLANES

Figure 13. Image processing using degenerate four wave mixing.

IMAGE PROCESSING USING DFWM



$$E_c \propto E_p^* E_1 E_2$$

$\therefore \; e_c \propto e_p \odot e_1 * e_2$ $\odot$ – correlation

$*$ – convolution

FOR e_c TO BE THE CORRELATION OF e_p AND e_1; e_2 MUST BE A δ - FUNC $\Rightarrow$ E_2 IS A PLANE WAVE

THEN

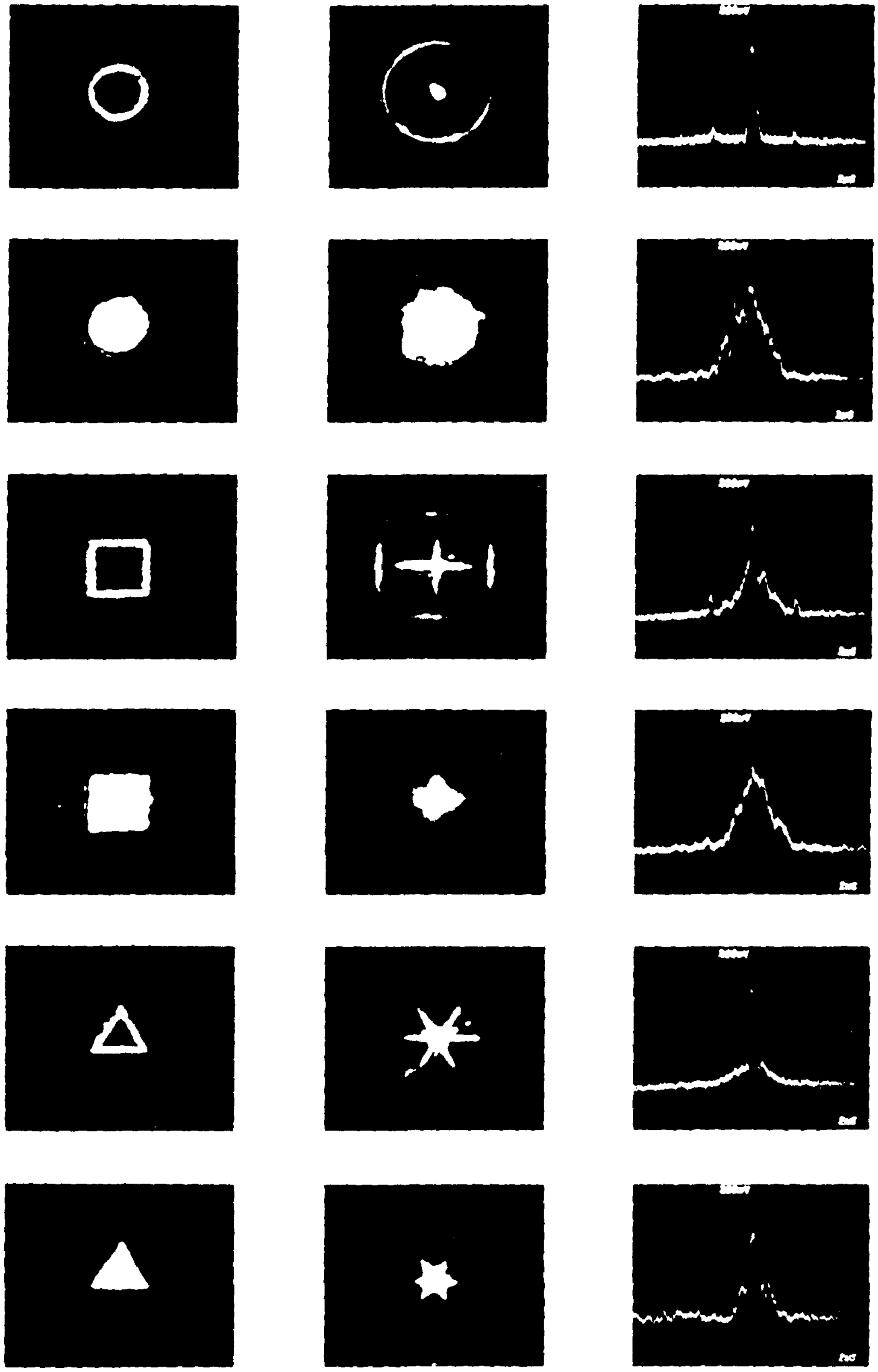
$$\underline{\underline{e_c \propto e_p \odot e_1}}$$

THIS SYSTEM IS SPATIALLY INVARIANT
NOT SCALE INVARIANT
NOT ROTATION INVARIANT

Figure 14. Autocorrelation obtained using degenerate four wave mixing. The simple geometric shapes used as the initial objects in planes e_1 and e_p (Figure 13) are shown in the left hand column. The autocorrelation function is given for these shapes in the middle column and a cross-section through the autocorrelation in function given in the right hand column.

AUTOCORRELATION FUNCTIONS OBTAINED USING DEGENERATE FOUR WAVE MIXING

IMAGE CORRELATION



REAL TIME EDGE ENHANCEMENT USING
DEGENERATE FOUR WAVE MIXING

ORIGINAL IMAGE

EDGE ENHANCED IMAGE

Figure 15. Real time edge enhancement using degenerate four wave mixing. The edge enhanced image is obtained by setting the relative intensities of the beams in the correct ratio as described in the text.

REAL TIME EDGE ENHANCEMENT USING DEGENERATE FOUR WAVE MIXING

ORIGINAL IMAGE | EDGE ENHANCED IMAGE

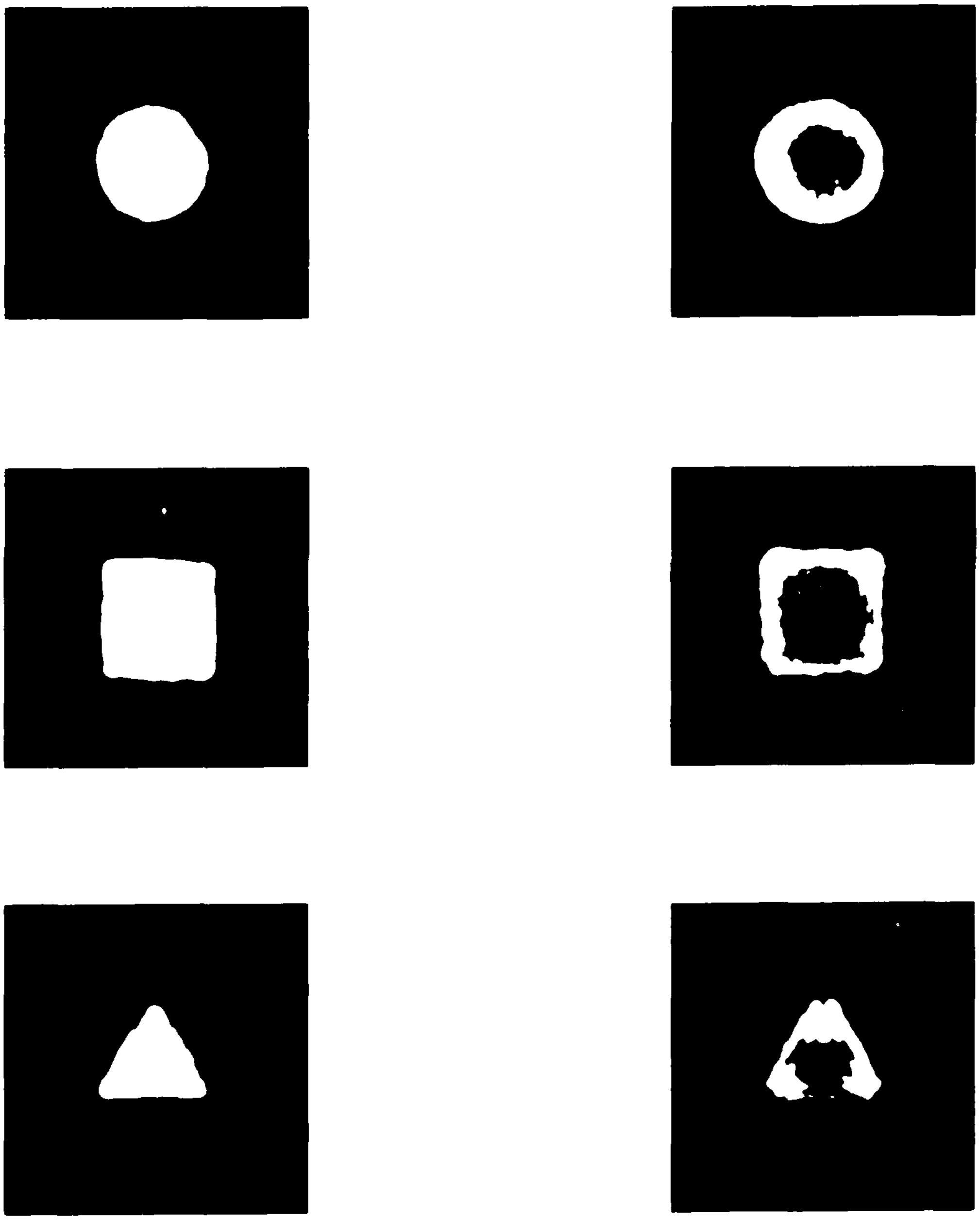


Figure 16. Time delay control of one optical pulse with another using a non-linear delay line. The inputs E_p and E_l are co-polarised while the pulse to be controlled is orthogonally polarised.

TIME DELAY CONTROL OF OPTICAL PULSES USING OPTICAL PHASE CONJUGATION

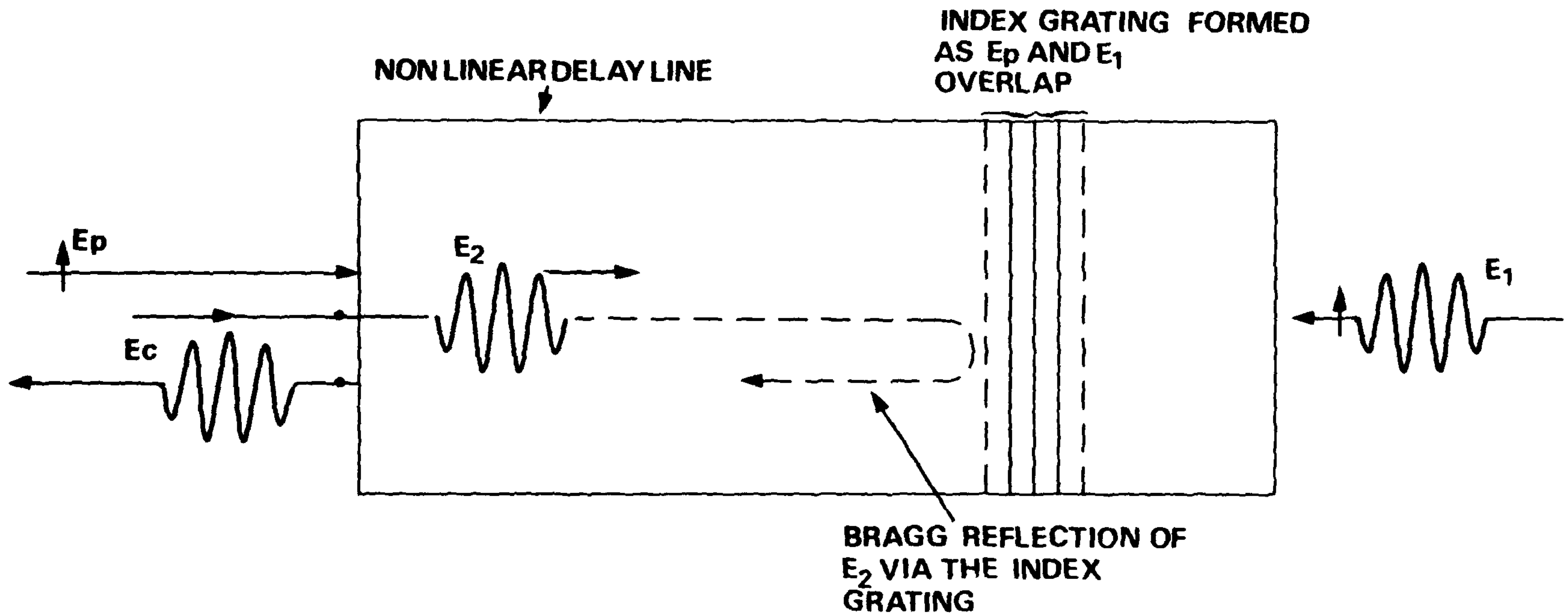
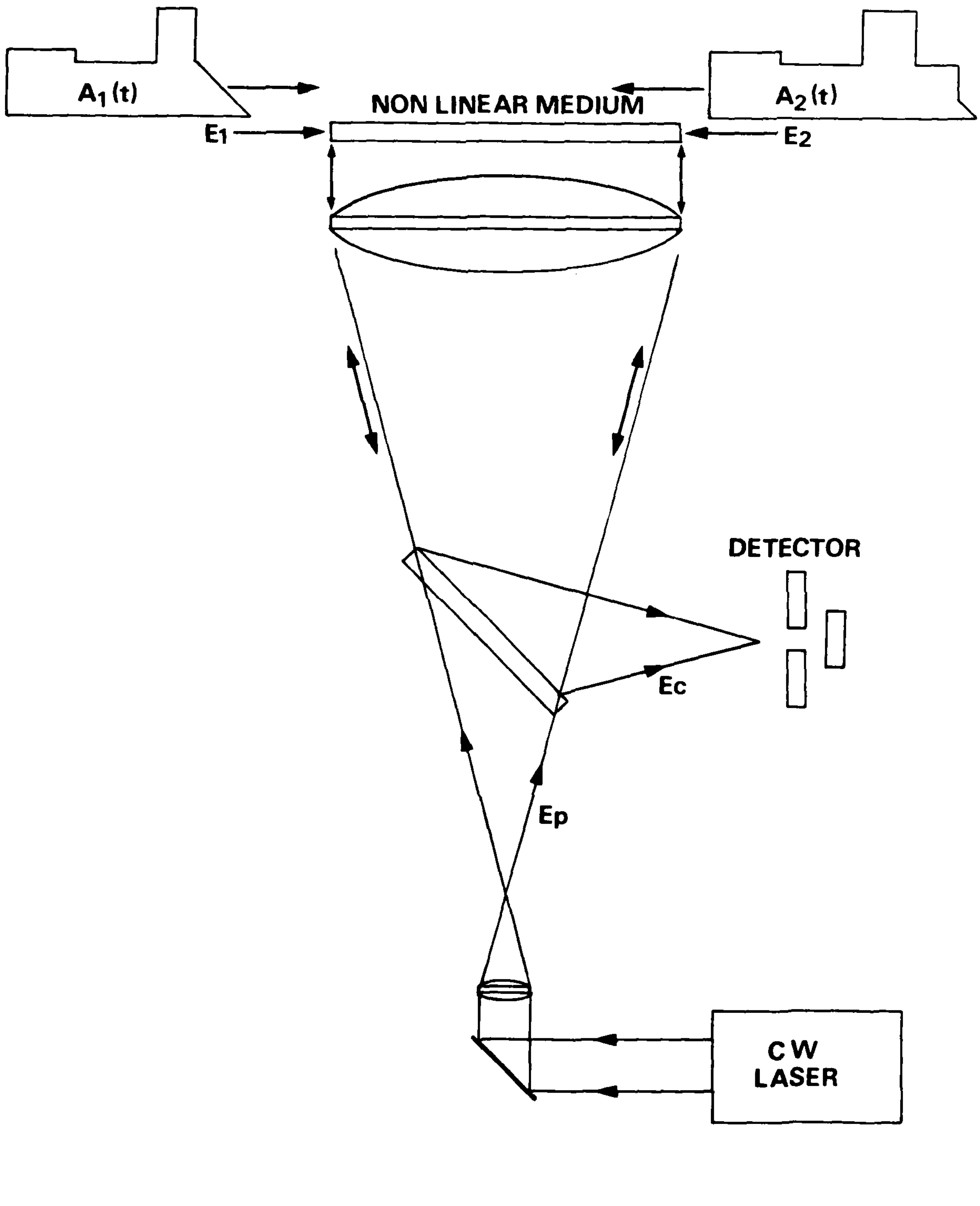
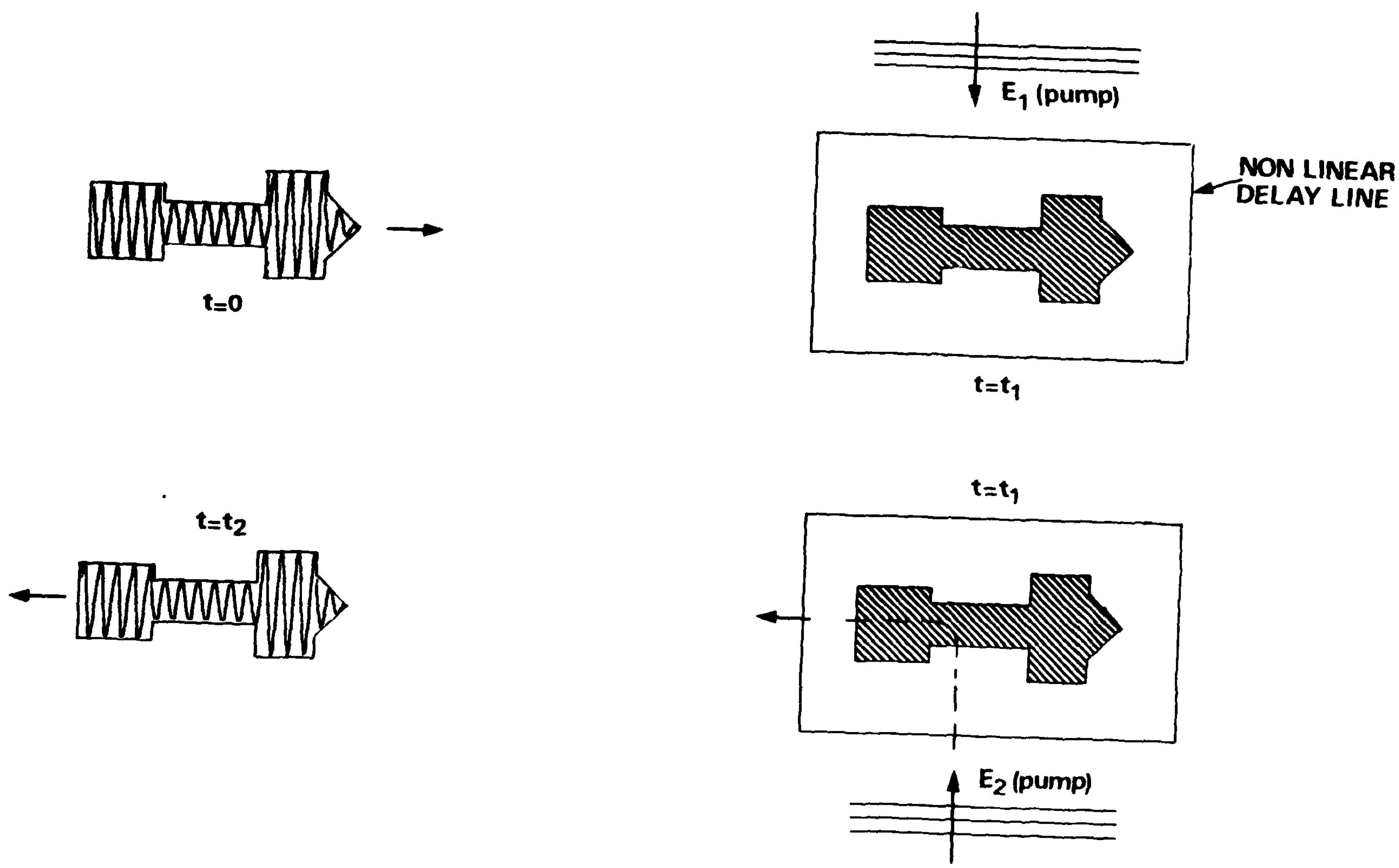


Figure 17. Time domain correlator using degenerate four wave mixing. The modulation envelopes $A_1(\tau)$, $A_2(\tau)$ are cross-correlated in the nonlinear slab as they pass each other. The detector output gives the correlation function as a function of time.



TIME DOMAIN CORRELATOR

Figure 18. Wave train reversal using degenerate four wave mixing. A holographic fringe pattern is written into the nonlinear delay line with an amplitude which is modulated by the input wave train amplitude. A second pump pulse is scattered off this fringe pattern when one reconstitutes the original wave but in a time reversed sense.



WAVE TRAIN TIME REVERSAL USING OPTICAL PHASE CONJUGATION

Figure 19. Spatial to temporal encoding using four wave mixing. In this example a parabolic spatial phase encoding in pump E_2 scatters off an index grating formed by the beat between probe E_p and pump E_1 to become temporally encoded as a chirp.

SPATIAL TO TEMPORAL OPTICAL ENCODING

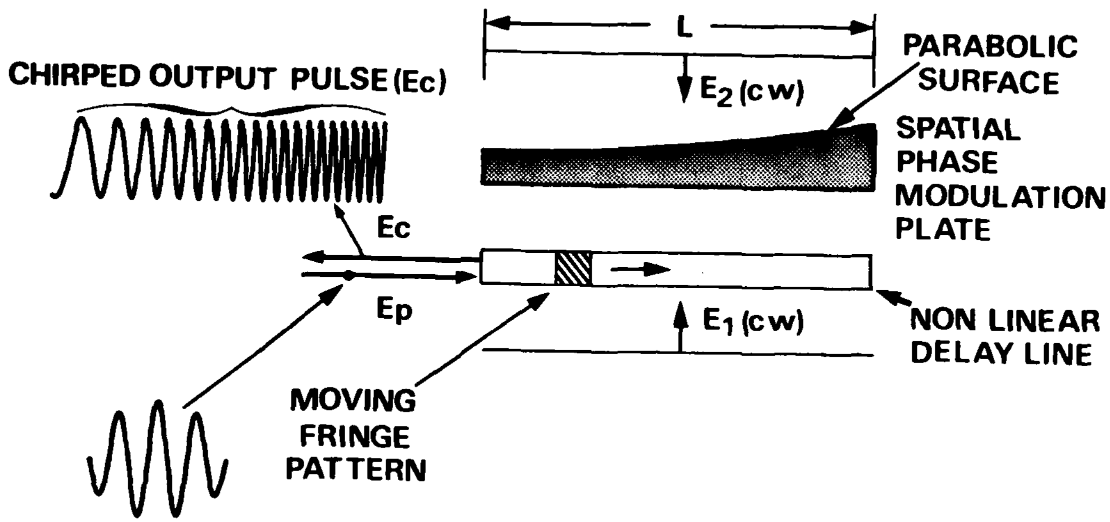


Figure 20. Covert communication using four wave mixing. A time encoded signal on pump 1 or 2 can be accessed using a probe beam. The return beam is time encoded and is counter-propagating with respect to the probe. If the system is configured so that pump 2 and the probe beam are coherent the only limitation to the bandwidth of the system is the interaction time within the nonlinear medium.

COVERT COMMUNICATION

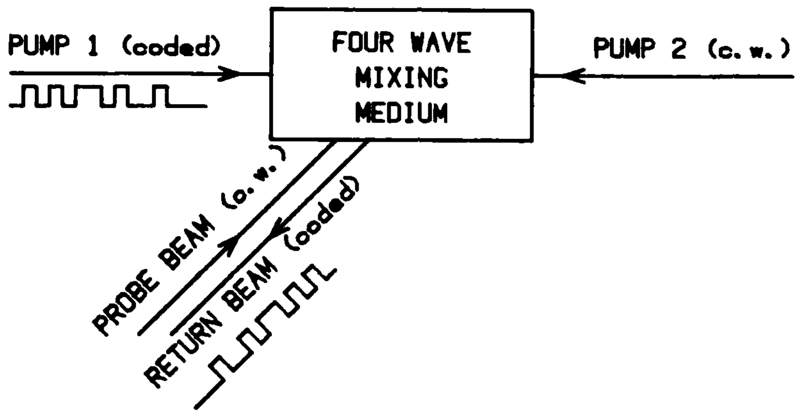
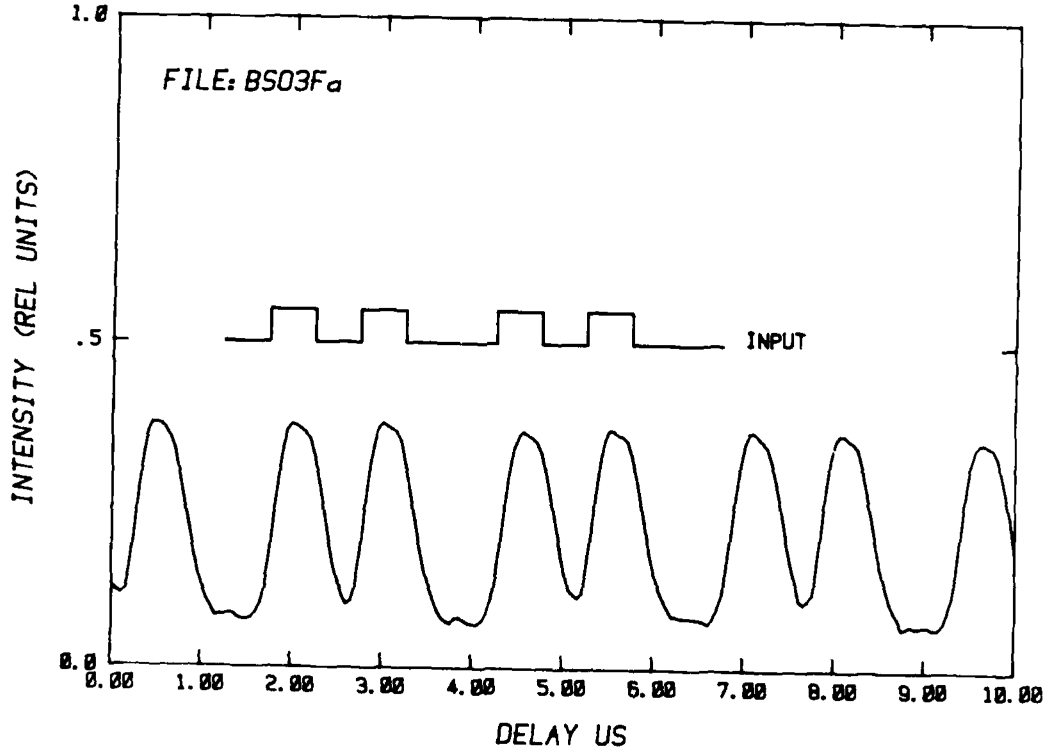


Figure 21. Megahertz data rate transmission demonstrated using the system described in Figure 20. The bandwidth of the optical modulator and detector limit measurement to that displayed in the figure. Transmission rates in excess of 1 GHz are conceptually possible.


FILE: BSO3Fa
INTENSITY (REL UNITS)
1.0
.5
0.0
INPUT
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
DELAY US

APPENDIX A - ALTERNATIVE TECHNIQUES FOR NONLINEAR OPTICAL PHASE CONJUGATION

THREE WAVE MIXING

In three wave mixing two intensely monochromatic input fields fall on to a crystal which lacks inversion symmetry. A conjugate replica of the probe beam can occur if the material has a non-zero second order nonlinear optical susceptibility, $\omega_c = \omega_1 - \omega_p = \omega_p$ ($\omega_1 = 2\omega_p$) and $\underline{k}_c = \underline{k}_1 - \underline{k}_p$. This interaction can only occur along one direction and the phase matching constraint causes a severe limitation on the acceptance angle of the device. The interaction has been demonstrated with probe (1.06 m) and pump (0.53 m) derived from a Nd:YAG laser(32).

FOUR WAVE MIXING

In four wave mixing three input fields fall on to the nonlinear median which has a non-zero third order susceptibility. Ther are no symmetry limitations to the type of crystal that may exhibit this effect unlike in three wave mixing. In general all waves are considered to be identical in wavelength and a fourth wave may be radiated which is conjugate to the probe beam if the two pump beams are counter-propagating. In this case (described in the text) a backward going phase conjugate is generated. This process is independent of the input angle of the probe wave and does not exhibit the same rigorous phase matching constraints described above.

It is possible using four wave mixing to generate a forward going phase conjugate replica of the probe beam. In this case the pump beams are co-propagating and the conjugate wave radiate in a direction given by $\underline{k}_c = 2\underline{k}_1 - \underline{k}_p$. In this case there are phase matching constraints which limit acceptance angles.

In non-degenerate four wave mixing the four beams do not have perfectly identical optical frequencies. In this case the wavelength detuning of the probe beam from that frequency corresponding to the pump results in a quick loss of efficiency of the phase conjugate reflector(33). The effect can demonstrate a high Q optical filtering function for the probe light.

OTHER NONLINEAR OPTICAL PHOTON INTERACTIONS BASED ON ELASTIC SCATTERING

The two cases considered above are the result of "Kerr-like" nonlinearities (based on the nonlinear complex refractive index) which may result from molecular re-orientation effects(25,34), saturation(35) or band structure effects(4,36). Other techniques invoke transient optical excitation processes like the giant dipole(23). In this interaction the atomic dipole moments rephase in time and space to give an echo which may be generated in the forward or reverse direction(37). Nonlinear optical phase conjugation can also be demonstrated using self induced, volume saturation effects(38), plasmas(39), non-local field effects(40), thermal effects(41) and surface effects(42,43).

NONLINEAR OPTICAL PHASE CONJUGATION USING INELASTIC PHOTON SCATTERING

In all above set of techniques of elastic photon scattering no energy was transferred to the nonlinear medium. In a second set of mechanisms that can result in nonlinear optical phase conjugation the process is inelastic and some energy is transferred to the nonlinear medium (eg Raman, Brillouin[48] and Rayleigh scattering[46,47]. The transferred photon energy can be in the form of acoustic phonons, collective pressure density fluctuations, optical phonons or molecular vibrations. The medium gives rise to a frequency down-shifted, backward going, phase conjugate replica of the incident wave. The Stokes wave is frequency down-shifted by $\sim 1\ cm^{-1}$ for Stimulated Brillouin Scattering (SBS) (Refs 1,28,45,46) and by $\sim 1000\ cm^{-1}$ for Stimulated Raman Scattering (SRS)[1,49,5.0]. In these interactions it is necessary to overcome a critical input intensity before phase conjugation is observed (not required in the elastic scattering) and the reflectivity of this process is always less than one (in DFWM they may be configured to exceed unity). The advantage of these techniques is that the reflector is passive and no auxiliary pump beams are required (with the necessary coherence length constraints, alignment, spatial filtering etc). Thus these techniques seem promising in high power pulsed laser systems.

APPENDIX B - SUMMARY OF EXPERIMENTS WHERE CONJUGATE REFLECTIVITY WAS MEASURED[1]

In all the experiments the lasers were CW and the interaction employed was Degenerate Four Wave Mixing.

Wavelength	Nonlinear Medium	Comments (R,I,L)	Reference
10 m	SF_6	0.19%, 7 W/cm^2, 10 cm	51
	HgCdTe	1.2%, 10 W/cm^2, 0.36 mm, 77K	52
5.3 m	InSb	1%, 13 mW, 5K	53
632.8 nm	$BaTiO_3$	> 100%, 1 mW, 3 mm	1
	BSO		
589 nm	Na vapour	150% narrowband	54
488 nm / 514.5 nm	Ruby	~ 0.2%	55
	BSO/BGO	~ 1% slow photorefractive	56/6
	$BaTiO_3$	> 100% slow	57
	Liquid Crystals	~ 0.1% slow	1
	CS_2	~ 0.5% waveguide	58
	Aerosol	~ 0.5% slow electrostrictive	59
441.6 nm	Liquid Crystals	1%, 10 W, slow	60
413.1 nm	$LiNbO_3$	slow	61

UNLIMITED

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	Memorandum 3856		U/C

5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location
	Royal Signals and Radar Establishment
5a. Sponsoring Agency's Code (if known)	**6a. Sponsoring Agency (Contract Authority) Name and Location**

7. Title

APPLICATION OF PHASE CONJUGATION TO IMAGE AND SIGNAL PROCESSING

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers) Title, place and date of conference

8. Author 1 Surname, initials	9(a) Author 2	9(b) Authors 3,4...	10. Date	pp. ref.
West C L				

11. Contract Number	12. Period	13. Project	14. Other Reference

15. Distribution statement

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Abstract

Some of the many potential applications of optical phase conjugation include real time adaptive optics, optical signal processing (in the time or spatial domain), image processing and optical computing. Some of the salient features of optical phase conjugation and the more important signal and image processing functions that one may demonstrate using these techniques will be described in this Memorandum.